The impacts of climate change on terrestrial ecosystems

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Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analyses

Washington, DC

January 27-28, 2011

1. Background

Concerns over the impacts of rising global atmospheric greenhouse gas (GHG) concentrations are growing. Although human welfare and well-being will be directly affected by changes in climate, many important impacts to human welfare will occur indirectly due to climate-induced changes in ecosystems. Terrestrial ecosystems provide critical goods and services to humans. For example, they provide raw materials (e.g., food, water, and timber), regulate air quality, assimilate waste, and provide recreational opportunities. Terrestrial ecosystems are also valuable simply for existing; that is, society puts value on the existence of species and habitats and invests resources to protect them. To fully understand the benefits and costs of alternative climate policies, increases or declines in these critical services resulting from climate change must be evaluated.

It is well understood that climate is a key determinant of the structure and function of ecosystems. Climate affects which species are able to reside in a given location, how productive an ecosystem is, the rates of ecosystem processes (e.g., nitrification, methane production), and the nature, frequency, and intensity of natural disturbances (e.g., wildfires, pest outbreaks). Thus, as climate changes, it will fundamentally, and potentially dramatically, affect the location and character of ecosystems.

Which ecological impacts should be examined?

The Intergovernmental Climate Change reports, U.S. Climate Change Science Program synthesis reports, and a variety of other synthetic reports issued by states, governments, and NGOs provide a long list of potential impacts to terrestrial ecosystems. The impacts range across geographic scales (i.e., some are sub-national, country-specific, or global) and across different levels of biological organization (i.e., some address individual species, ecosystems, or global biodiversity). Which of these myriad of impacts should be addressed in integrated assessment models? I suggest that the focus be on impacts that are:

- Ecologically important – the impact is large and relatively widespread geographically

- Economically important – the impact will affect ecosystem services with high economic values

- Well understood – one needs to be able to project the magnitude of the impact in a scientifically robust manner.

2. Key terrestrial ecosystem impacts

Neither this abstract, nor the oral presentation that accompanied it, is intended to provide a comprehensive overview of terrestrial climate change impacts. Rather, I intend to highlight some of the key impacts and related tools that either have been or could be incorporated into integrated assessment models. Specifically, I discuss three large-scale terrestrial ecosystem impacts: (1) changes in vegetation distribution and dynamics, (2) changes in wildfire dynamics, and (3) potential increases in species extinction risks.

2.1 Changes in vegetation distribution and dynamics

Why climate change will affect vegetation dynamics. Climate is a fundamental driver of key ecological properties and processes. Temperature, precipitation, and relative humidity (and other climatic variables) affect where species can persist, ecosystem productivity, rates of ecosystem processes (e.g., organic matter decomposition), and frequency and intensity of disturbance events (e.g., wildfire, droughts, and pest outbreaks). Changing climate will thus fundamentally affect our environment, changing where grasslands and forests are located, the productivity of ecosystems, and kinds of disturbance regimes ecosystems experience.

Tools used to project changes in vegetation. Dynamic global vegetation models (DGVMs) are the most commonly used tool to project future changes in vegetation. Although many different models exist, typically all of them can address three specific issues: (1) how soil and climate affect the distribution of vegetation types, (2) how nutrients move within a given geographic area, and (3) wildfire dynamics. For a specific time period and climate change scenario, DGVMs can provide information about the potential distribution of vegetation types, the biomass of different types of vegetation (e.g., tree, shrub, grass), terrestrial carbon storage, and the frequency and extent of wildfires.

Examples of recent research. There has been a large volume of DGVM-related research over the past decade, and it is beyond the scope of this abstract to capture the history and evolution of that research. However, I will note that recent studies have used DGVMs to examine the impact of climate change on vegetation dynamics in specific countries, regions, and globally. For example, Lenihan et al. (2008) used the MC1 DGVM to demonstrate that there may be rather significant shifts in the distribution of vegetation in the United States by 2100 under climate change scenarios (based on the SRES A2 and B2 emissions scenarios). This study also showed that the extent of change in vegetation type and carbon storage is heavily influenced by fire suppression. Sitch et al. (2008) examined the potential impact of climate change on global vegetation and compared results across five DGVMs and four different SRES emissions scenarios. Their results

showed substantial differences across models in vegetation responses to drought in the tropics and warming temperatures in boreal ecosystems. In this study, for all but the most extreme SRES scenarios (A1FI), the DGVMs suggested that the terrestrial biosphere would continue to be a sink throughout the 21st century. The stimulative effect of elevated CO_2 compensated for the direct suppressive effects of climate change on terrestrial carbon uptake. Galbraith et al. (2010) assessed the extent of projected Amazon forest die-back under future climate change using three DGVMs and the Hadley climate model (HadCM3). All DGVMs showed some degree of die-back, but the extent and intensity of the die-back varied significantly across DGVMs. Importantly, the models varied in their sensitivities to changes in rainfall and temperature; one model was equally sensitive to both changes in precipitation and temperature, but the other two were strongly affected by changes in temperature and insensitive to changes in precipitation.

Key uncertainties and shortcomings in projections of vegetation change. DGVMs can provide insights into the nature and magnitude of potential climate change impacts on terrestrial ecosystems, but there are important sources of uncertainty that should be kept in mind. First, these models provide information about "potential" vegetation only, ignoring the very real and critical impact that human intervention can have on the composition and productivity of vegetation. One can address fire suppression in DGVMs, and one can also screen out current and future urban and agricultural areas, but other effects (e.g., direct plantings, fertilization, invasive species) will be ignored. Second, many DGVMs assume there are no barriers to plant dispersal. This is clearly not the case, particularly in highly fragmented urban or agricultural landscapes. Third, the impacts of pests and pathogens are ignored, despite how critical these disturbance agents can be to shaping ecosystems. Finally, results across DGVMs can vary substantially for the same region and the same climate change scenario.

Affected ecosystem services. Changes in vegetation will affect a multitude of ecosystem services. Among the most important will be the provisioning of timber and non-timber forest products, grazing, and carbon storage and sequestration, which are critical to understanding potential terrestrial feedbacks to anthropogenic climate change.

2.2 Changes in wildfire frequency

Why climate change will affect wildfire frequency. Fires are likely to increase in many areas due to both the direct and indirect effects of climate change. Higher temperatures will directly increase the likelihood of fires – a spark is more likely to turn into a fire when temperatures are hotter. Higher temperatures also desiccate vegetation and forest floor, which provide the fuel for fires. Indirect effects on fire can be brought about via changes in vegetation. For example, grasslands burn more readily than forests. And changes in productivity affect fuel load.

Tools used to project changes in wildfire. In my review of the literature, I identified two main approaches to projecting wildfire under climate change. The first is to use statistical modeling. This involves examining past fire behavior and identifying the factors that best predict historical fire outbreaks (e.g., via step-wise linear regression). Changes in these factors are then used to

predict fire behavior in the future. The second approach involves utilizing the relatively simplistic fire models embedded in DGVMs to project future fire dynamics.

Examples of recent research. As with the review of dynamic global vegetation modeling, this section is not at all meant to be comprehensive, but rather to highlight studies that demonstrate the kinds of analysis that can be (and have been) done in this field recently. Many studies have been done at relatively small scales or at the country level, but here I'll mention two global studies, as that is the scale most relevant for integrated assessment models. Gonzales et al. (2010) used output from the fire model of MC1 to develop estimates of changes in fire frequency between 2000 and 2100 under SRES scenario A1B. They found the fire frequency decreased on two-fifths of global land, just slightly more than the area experiencing increases. Areas with potentially lower fire frequencies included the coterminous United States. and northern Eurasia; higher fire was projected for sub-Saharan Africa and northern South America. Krawchuk et al. (2009) used statistical modeling to estimate changes in fire probability under SRES scenarios A2 and B2. Some of their results agree with Gonzales et al. (2010) – decreases in fire probabilities are projected in northern Eurasia and higher fire probabilities are projected for South America. However, Krawchuck et al. (2009) found that fire probabilities would be higher in the United States and Europe and lower probabilities are estimated in sub-Saharan Africa.

Key uncertainties and shortcomings in projections of wildfire. For both statistical modeling and DGVM approaches to projecting future fire, the models only roughly approximate historical patterns of fire. They thus can only be expected to provide relatively rough indices of what might happen with fire in the future. Like DGVM studies, the results of fire modeling studies can vary significantly for the same region, and it is difficult for non-experts to assess which results are more accurate. Finally, the timing and location of specific fires cannot be projected – only rough approximations in overall changes in fire frequency and intensity for a given location can be provided.

Affected ecosystem services. Like changes in vegetation, fire will affect the provisioning of timber and non-timber forest products. Fire will also affect recreation, as people tend to stay away for a period of time from areas that have recently burned before they return to hike, fish, or camp. Although not an ecosystem service, changes in fire dynamics could also affect the amount of money that is spent on fire suppression, an effect not likely addressed by other sectoral analyses addressed in integrated assessment models. Finally, wildfire could have important effects on air quality via the release of aerosols, which would have important health and visibility implications.

2.3 Potential increases in species extinction risks

Why climate change will affect species extinctions. As noted earlier, climate is a critical driver of where different species and ecosystems are found. As climate shifts, the areas providing the climatic conditions that a species requires may move, sometimes into areas that don't have any habitat that could support that species (e.g., into agricultural or urban areas). It is also possible

that the climatic conditions a species requires may disappear altogether. This is more likely to occur with species that live at high altitudes or latitudes.

Tools used to project changes in species extinction risks. There are a variety of approaches that can be used to estimate the risk of future species extinctions. However, the most commonly used approach involves the application of climate envelope models. These models use information about the current distributions of species and the associated range of climate conditions to construct their climate requirements. Under future climate scenarios, one estimates where that species could live and how much area is available to it. Some studies then use species-area relationships (species diversity is known to increase with size of geographic area) to determine how many species can be supported in a future climate. Climate envelope models can be used alone or in conjunction with expert opinion to estimate species extinction risks. Another, less commonly used approach for examining future extinction risks involves utilizing vegetation models to estimate habitat loss within a specific geographic area under different climate change scenarios; such analyses often make the simplifying assumption that species ranges cannot shift to accommodate changes in habitat (Pereira et al., 2010).

Examples of recent research. Estimates of species extinctions vary widely. For example, Thomas et al. (2004) estimate that between 9 and 52% of species would be committed to extinction by 2050, depending on the assumptions made about dispersal ability and the specific climate change scenario. The IPCC (2007a) estimated, using a combination of expert judgment and information from climate envelop studies, that 20 to 30% of plant and animal species would be at risk of extinction with an increase of 2 to 3ºC in global temperature. A range of studies, using quite different methodologies and examining different taxa, found that from 0 to 60% of species may be at risk of extinction under future climate change (Pereira et al., 2010). Interestingly, Beale et al. (2008) found that climate envelop models did no better than chance in explaining why species reside where they do for approximately two-thirds of European bird species.

Key uncertainties and shortcomings in estimates of future extinction risks. Although climate change poses a real, critical threat to species across the globe, there is a great deal of uncertainty both within and among modeling studies about the magnitude of climate change impact on species extinctions. Climate envelope models are known to have some specific technical issues; these issues need to be specifically addressed because these types of models are used so often. First, they may overestimate extinctions because species may be more flexible climatically than their current distribution suggests. Envelope models may also underestimate extinctions because climate change may interact with other factors, making things worse than predicted. For example, some species may not be able to persist near human settlements even if the climate is suitable.

Affected ecosystem services. Understanding the economic impact of global-level species extinctions is another challenge. Economic studies have been done to estimate the existence values of species, but these studies can be highly controversial. The impacts of extinctions on other services could be explored, given the services that specific species or suites of species can provide. For example, a tree species may provide valuable wood, and bird and wildlife viewing

provide another type of value. However, such values are typically tied to species or geographic locations rather than global extinctions, making this approach impractical.

3. Future research needs

3.1 Integrating across studies

Across all ecosystem impacts, there are a variety of methods available to project future dynamics, and the methods typically give different answers regarding the magnitude of the impact in question. The question is – how should all the different tools and studies be integrated? Some ideas include:

- Conducting meta analyses, which involves pooling data across many studies to detect general patterns.
- Developing ensemble means, as is done for climate models, across different impact models. This approach would likely require ensembles to be developed across different climate change scenarios and GCMs, making its feasibility questionable.
- Soliciting expert opinions. Although imperfect and subjective, this is a cost-efficient method for providing rough estimates of the potential direction and rough magnitude of specific impacts.

3.2 Key knowledge gaps

There are also some critical knowledge gaps that need to be addressed when considering the kinds of impacts that would appropriately be addressed in integrated assessment models. Three key gaps include:

- Pest outbreaks. There is a dire need for models that project the impact of climate change on pest outbreaks. We know that pests are critical drivers of the productivity and structure of ecosystems and that they will have significant impacts on the provisioning of ecosystem services.
- Freshwater wetlands. Large-scale, interior, freshwater wetlands provide critical ecosystem services, and it is clear they will be affected by changes in precipitation and temperature. Although some models have been developed to conduct sensitivity analyses related to wetland impacts, projections of impacts for specific regions (e.g., the Prairie Pothole region) are needed.
- Snow pack dynamics. A lot of research has examined the impact of climate change on snow pack dynamics, but this research has typically focused on water resource implications. Changes in snow pack volume and the timing of snow pack melt can affect freshwater and marine ecosystems as well as snow-related recreation.

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